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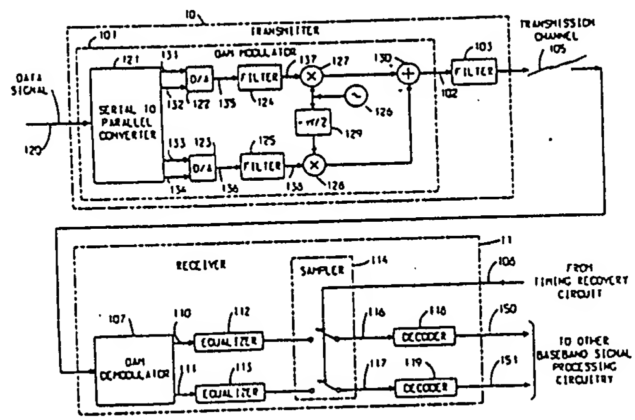

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(57) Abstract

A bandwidth reduction technique for use in digital systems wherein elements of a data signal modulate quadrature-related carriers. This modulation, referred to as quadrature amplitude modulation (QAM) or phase shift keying (PSK), generates a double-sideband signal which is transmitted in a variety of communications systems. In accordance with the present invention, the above-described double-sideband signal is filtered (103) to form a single-sideband signal prior to transmission. While this use of a single-sideband signal, in lieu of a double-sideband signal, effectively doubles the system capacity by permitting the use of two communications systems in the bandwidth previously occupied by one system, the filtering process (103) contaminates the data signal elements. To recover the data signal elements at the receiver, received signal elements are formed by extracting the carrier signals (107). Next, these received signal elements are altered by preselected quantities to form estimates of each data signal element (301, 302...307). A comparison of the formed estimates (318) against the set of permissible values for each data signal element then determines which estimate is correct.

SINGLE-SIDEBAND COMMUNICATION SYSTEM

Technical Field

The present invention relates to a digital communications system which transmits a single-sideband signal comprising modulated quadrature-related carriers.

Background of the Invention

Digital communication systems utilize a myriad of modulation formats. In one commonly-used format, elements of a data signal modulate quadrature-related carrier signals. This type of modulation has a variety of names, such as phase shift keying (PSK), quadrature amplitude modulation (QAM), and asynchronous phase shift keying (APSK). The information conveyed by the data signal is, of course, virtually limitless and can include voice, video, facsimile and the like. Moreover, the transmission channel carrying the modulated carriers is also not limited and, at present, may include air, wire or lightguide.

A problem in practically all communications systems is that the transmission channel is band-limited. That is, there is a finite frequency interval which can be used to convey information. This limitation arises because of system and/or device requirements. While the severity of this problem does vary from system to system, it still can be said that the ability to convey still more information in a given frequency interval would be highly desirable.

One technique to increase the information-carrying capacity of a digital system transmitting modulated quadrature-related carriers is to increase the number of permissible modulation states. An example of this technique is exemplified by the design and deployment of 64 QAM systems in lieu of 16 QAM systems in applications requiring greater capacity. The problem with this technique is that the change in the number of modulation states requires at least the design and development of new modulators and demodulators. This effort is often

expensive and the resulting equipment, at times, can not be retrofitted into operational systems without great expense.

Another technique to increase system capacity has been to utilize single-sideband signals instead of double-sideband signals. This technique is rather simple to implement and has been routinely used in formats which modulate a single carrier signal. Unfortunately, this technique has not been used for systems utilizing quadrature-related carriers because there was no known way of intelligently decoding the received signal after single-sidebanding.

Summary of the Invention

The present invention is intended for use in digital communications systems wherein elements of a data signal modulate quadrature-related carrier signals. To reduce the required bandwidth, the resulting modulated quadrature-related carriers are transformed into a single-sideband signal. After propagation through the transmission channel, the received single-sideband signal is demodulated into received signal elements. Each of these elements includes an element of the data signal along with a spurious signal introduced by the single-sideband transformation. To recover the data signal elements, each received signal element is altered to form at least one estimate of the corresponding data signal element. Each estimate formed is then compared against a set of permissible data signal element values and the estimate is outputted if a preselected criterion is met.

A feature of the present invention is that it can be implemented within existing digital communications systems to provide a substantial increase in information-carrying capacity within some preselected bandwidth.

A further feature of the present invention is that it can be used with conventional demodulation and equalization techniques.

Brief Description of the Drawing

FIG. 1 is a block schematic diagram of a

communications system which incorporates the present invention;

FIG. 2 is a plot of the signal space diagram of the signal levels transmitted by the communications system of FIG. 1; and

FIG. 3 is a detailed schematic diagram of decoders 118 or 119 shown in the communications system of FIG. 1.

Detailed Description

FIG. 1 shows an exemplary QAM communications system which incorporates the present invention. At transmitter 10, a digital data signal on lead 120 is coupled to QAM modulator 101. Within modulator 101, serial-to-parallel converter 121 spreads successive data signals on lead 120 over four paths 131,132,133, and 134. Digital-to-analog (D/A) converter 122 quantizes the signals appearing on leads 131 and 132 into a number of signal voltages which appear on lead 135. Similarly, D/A converter 132 quantizes the signals on leads 133 and 134 into a number of signal voltages which are coupled to lead 136. Multipliers 127 and 128 receive the signal voltages on leads 135 and 136 after they are respectively smoothed by Nyquist filters 124 and 125. Multiplier 127 modulates the amplitude of a carrier signal generated by oscillator 126 with the signals on lead 135 after filtering. In similar fashion, multiplier 128 modulates the amplitude of a second carrier signal with the signals on lead 136 after smoothing by Nyquist filter 125. The second carrier signal supplied to multiplier 128 is generated by shifting the carrier signal generated by oscillator 126 by minus $\pi/2$ radians via phase shifter 129. Hence, the pair of carrier signals supplied to multipliers 127 and 128 are in spatial quadrature to one another and the products provided by multipliers 128 and 129 are each double-sideband signals. Summer 130 then adds the products provided by multipliers 128 and 129 and outputs this sum, also a double-sideband signal onto

lead 102.

Reviewing the signal processing provided by the transmitter components discussed thus far, it can be said that these components modulate quadrature-related carriers with elements of a data signal, wherein one element of the data signal comprises the signals appearing on leads 131,132 or 135 or 137 while the other data signal element comprises the signals appearing on leads 133,134 or 136 or 138. In addition, if we select the number and permitted values of the signal voltages provided by D/A converters 122 and 123, we can graphically depict all of the possible combinations of transmitted carrier signal amplitudes which represent the data signal on a cartesian coordinate plot. Such a plot is commonly referred to as a signal space diagram.

Refer now to FIG. 2 which shows the signal space diagram for the illustrative transmitter of FIG. 1. The data signal element appearing on lead 137 is designated as the "I" or in-phase element of the data signal while the data signal element appearing on lead 138 is referred to as the "Q" or quadrature element. As shown, the permissible values of the "I" and "Q" elements are ±1 and ±3 volts and all possible combinations of these permissible values form 16 signal states, designated as 201, in FIG. 2.

In prior art communications systems, the output of summer 130 is coupled to a transmission channel which propagates the information to system receiver 11. In accordance with the present invention, a filter 103 is added to the transmitter to convert the double-sideband signal at the output of summer 130 into a single-sideband signal thereby reducing the bandwidth required for signal transmission. This bandwidth reduction also permits the transmission of a second single-sideband QAM signal in the recovered frequency interval. The resulting capacity of two 16 QAM single-sideband signals is equivalent to that of a 256 QAM double-sideband signal. The double-sideband to single-sideband signal conversion, however, corrupts the

operation of conventional QAM receiver circuitry and additional functional capability is required in the receiver to intelligently recover the data signal elements. At this juncture, it should be understood that the present invention is also applicable to radio systems wherein additional circuitry is often disposed between summer 130 and the transmission channel to shift the frequency of the transmitted carriers to a higher frequency band. Moreover, the present invention is not limited to QAM systems and, indeed, may be utilized in any system which transmits a signal comprising modulated quadrature-related carriers which are modulated in phase or amplitude or some combination of phase and amplitude.

To understand the principles of the present invention, it is first necessary to consider the effects of filtering one of the sidebands of the illustrative double-sideband QAM signal and then transmitting the resulting single-sideband signal through a transmission channel.

The QAM signal appearing at the output of summer 130 can be expressed as a function of time s(t) with

$$s(t) = i(t) \cos w_c t - q(t) \sin w_c t \ ; \qquad (1)$$

and where w_c denotes the frequency of the carrier generated by oscillator 126, and

$i(t)$ and $q(t)$ respectively denote the values of the I and Q data signal elements as a function of time.

When s(t) is passed through filter 103 with an impulse response h(t) in order to reject either one of the sidebands, we can express the resulting single-sideband signal as $[s(t)]_{SSB}$ with

$$[s(t)]_{SSB} = \int_{-\infty}^{+\infty} h(\tau) i(t-\tau) \cos[w_c(t-\tau)] d\tau - \int_{-\infty}^{+\infty} h(\tau) q(t-\tau) \sin[w_c(t-\tau)] dr \qquad (2)$$

and where τ represents a dummy variable of integration.

Using the trigonometric identities:

$$\cos[w_c(t-\tau)] = \cos w_c t \cos w_c\tau + \sin w_c t \sin w_c\tau \text{ and}$$
$$\sin[w_c(t-\tau)] = \sin w_c t \cos w_c\tau - \cos w_c t \sin w_c\tau, \quad (3)$$

equation (2) can be rewritten as:

$$\begin{aligned}[s(t)]_{SSB} = & \int_{-\infty}^{+\infty}\{h(\tau)i(t-\tau)\cos w_c\tau\, d\tau\}\cos w_c t \\ & + \int_{-\infty}^{+\infty}\{h(\tau)q(t-\tau)\sin w_c\tau\, d\tau\}\cos w_c t \\ & + \int_{-\infty}^{+\infty}\{h(\tau)i(t-\tau)\sin w_c\tau\, d\tau\}\sin w_c t \\ & - \int_{-\infty}^{+\infty}\{h(\tau)q(t-\tau)\cos w_c\tau\, d\tau\}\sin w_c t \qquad (4)\end{aligned}$$

Equation (4), in turn, can be written as:

$$\begin{aligned}[s(t)]_{SSB} = & \frac{1}{2}\{i(t) + \hat{q}(t)\}\cos w_c t \\ & - \frac{1}{2}\{q(t) - \hat{i}(t)\}\sin w_c t, \qquad (5)\end{aligned}$$

where $\hat{i}(t)$ and $\hat{q}(t)$ are the Hilbert transforms of $i(t)$ and $q(t)$, respectively.

A comparison of equation (5) with equation (1) reveals that the effect of eliminating one of the sidebands of the QAM signal of equation (1) contaminates $i(t)$ with the Hilbert transform of $q(t)$ and contaminates $q(t)$ with the Hilbert transform of $i(t)$. Consequently, the receiver of FIG. 1 must be provided with the capability of eliminating $\hat{q}(t)$ and $\hat{i}(t)$ to respectively recover the $i(t)$ and $q(t)$ components.

Refer back to FIG. 1 and consider the general case where transmission channel 105 is dispersive and introduces distortion comprising intersymbol interference (ISI), cross-rail interference (X-rail ISI) and Gaussian noise ($n(t)$). If $s(t)_{SSB}$ is coupled through a conventional QAM demodulator 107, two received data elements $i'(t)$ and $q'(t)$ are formed on leads 110 and 111. The generation of $i'(t)$ and $q'(t)$ is accomplished by extracting the quadrature-related carriers from the received signal using well-known carrier recovery

techniques. The signals on leads 110 and 111 can be expressed as:

$$i'(t) = [i(t) + \hat{q}(t)] + ISI + X\text{-rail } ISI + n_I(t) \quad , (6)$$

and

$$q'(t) = [q(t) - \hat{i}(t)] + ISI + X\text{-rail } ISI + n_Q(t) \quad , (7)$$

with $n_I(t)$ and $n_Q(t)$ respectively representing the Gaussian noise introduced into i(t) and q(t).

The ISI and X-rail ISI in equations (6) and (7) can be eliminated by coupling i'(t) and q'(t) through conventional transversal equalizers 112 and 113 which are configured to operate on i'(t) and q'(t) as if $[i(t) + \hat{q}(t)]$ and $[q(t) - \hat{i}(t)]$ were the information signals. The equalized signals $i_E(t)$ and $q_E(t)$ appearing at the output of equalizers 112 and 113 are then sampled at the baud rate, 1/T, by sampler 114. The k^{th} sample, where K is any integer, can be expressed as

$$i_E(kT) = [i(kT) + \hat{q}(kT)] + n_{IE}(kT) \qquad (8)$$

for lead 116 and

$$q_E(kT) = q(kT) - \hat{i}(kT) + n_{QE}(kT) \qquad (9)$$

for lead 117. The expressions $n_{IE}(kT)$ and $n_{QE}(kT)$ represent the Gaussian noise in the received signal components after equalization. Sampler 114 is controlled by a timing signal on lead 108 which is supplied by conventional timing recovery circuitry (not shown) in the receiver.

To recover the information carrying components of i(kT) and q(kT), $\hat{q}(kT)$ and $\hat{i}(kT)$ must be eliminated. It can be shown that $\hat{q}(kT)$ and $\hat{i}(kT)$ can only assume a limited number of values and the values are a function of the quantized values provided by D/A converters 122 and 123. The set of values for $\hat{i}(kT)$ and $\hat{q}(kT)$ for any communications system utilizing Nyquist filtering can be expressed as

$$\hat{i}(kT) = -1/2q((k-1)T) + 1/2q((k+1)T) \qquad (10)$$

and

$$\hat{q}(kT) = -1/2i((k-1)T) + 1/2i((k+1)T). \quad (11)$$

That is, the Hilbert transform of i(t) at the k^{th} sampling time is a function of q(t) at the (k-1) and (k+1) sampling times wherein the (k-1) and (k+1) sampling times are respectively one sampling time immediately preceding and one sampling time immediately succeeding the k^{th} sampling time. And, the Hilbert transform of q(t) at the k^{th} sampling time is a function of i(t) at the (k-1) and (k+1) sampling times wherein the (k-1) and (k+1) sampling times are respectively one sampling time immediately preceding and one sampling time immediately succeeding the k^{th} sampling time.

From equations (10) and (11), it follows that in the illustrative 16 QAM communication system wherein i(t) and q(t) can take on the values of $\pm$ 1 and $\pm$ 3 volts, $\hat{i}(kT)$ and $\hat{q}(kT)$ can take on any value from the set {0, -1, -2, -3, 1, 2, 3}. Therefore, at any sampling instant, kT, $\hat{i}(kT)$ and $\hat{q}(kT)$ can assume one of seven possible values.

Refer now to FIG. 3 which shows a detailed schematic of the circuitry within decoders 118 and 119 of FIG. 1. In decoder 118, the k^{th} sample $i_E(kT)$ is supplied to seven summers 301, 302, ... 307 to form seven estimates of i(kT) on leads 311 through 317. Each summer forms one of these estimates by subtracting a different one of the seven possible values of $\hat{q}(t)$ from $i_E(kT)$. Each of leads 321-327 supplies a different value of $\hat{q}(t)$ from a source of reference voltages (not shown). Selection circuit 318, comprising multiple threshold detectors, compares each estimate against the permissible values of i(t), namely, $\pm$ 1 and $\pm$ 3 volts, and selects the estimate of i(kT) which is closest to any of the permissible values. This selected estimate is outputted on lead 150. Decoder 119 performs an identical operation on each sample $q_E(kT)$, with the estimate of q(kT) closest to one of the permissible values of q(t) being outputted on

lead 151 in FIG. 1. As shown, leads 150 and 151 couples the selected estimates of i(t) and q(t) to timing recovery and other receiver circuitry for further signal processing not connected with the present invention.

In the process of estimate formation and selection, it is possible for ambiguities to arise, i.e., there are two or more estimates formed which are equally close to different permissible data element values. This problem can be avoided by using one set of values for i(t) and a different set of values for q(t). For example, for the illustrative 16 QAM signal constellation shown in FIG. 2, values of i(t) equal to $\pm$ 1 and $\pm$ 3 volts and the values of q(t) equal to $\pm$ 1.5 and $\pm$ 4.5 volts provide signal states 201' which circumvent the aforesaid ambiguity problem.

While the disclosed decoders 118 and 119 comprise circuitry which simultaneously provides seven possible estimates of i(t) and q(t) using parallel signal processing, the decoders could comprise only one adder which sequentially forms seven estimates of i(t) or q(t). In this approach, selection circuit 318 compares each estimate against the permissible values of a data element and any estimate which falls within a predetermined interval surrounding each permissible value would be outputted. Upon selecting an estimate, selector circuit 318 would inhibit the outputting of any other estimate until the next sample is received from sampler 114.

It should, of course, be understood that the present invention is not limited to the particular embodiment disclosed and that numerous modifications will occur to those skilled in the art which are within the spirit and scope of the invention. First, for example, the use of transversal equalizers in the receiver is not required if the magnitude of ISI and X-rail ISI is not large relative to the difference between permissible data element values. This is often true in lightwave and wire

systems wherein the transfer function of the transmission channel is not time-varying. Second, while Nyquist filters are only shown in transmitter 10, half-Nyquist filters could also be utilized in transmitter 10 and receiver 11.

Claims

1. Receiver apparatus for use in a digital transmission system wherein elements of a data signal modulate quadrature-related carriers and wherein said carriers are transformed into a single-sideband signal, said receiver apparatus comprising

means for demodulating said single-sideband signal to form received signal elements by extracting said quadrature-related carriers, said received signal elements being different from said data signal elements due to the transformation of said carriers into a single-sideband signal; and

means for recovering said data signal elements by forming at least one estimate of each of said data signal elements by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

2. The apparatus of claim 1 wherein said estimate formed for each of said data signal elements involves altering a different one of said received signal elements.

3. The apparatus of claim 2 wherein said recovery means forms said estimate at selected times.

4. The apparatus of claim 1 wherein each of said data signal elements have specific assigned values.

5. The apparatus of claim 4 where said assigned values for all data signal elements are the same.

6. The apparatus of claim 4 wherein said assigned values for one data signal element are different from said assigned values for any other data signal elements.

7. The apparatus of claim 4 wherein said preselected quantity is a function of the assigned values.

8. The apparatus of claim 7 wherein said function forms a set of numbers which comprises said preselected quantity.

9. The apparatus of claim 1 wherein each

received signal element includes one data signal element and a nonzero function of another data signal element.

10. The apparatus of claim 9 wherein said nonzero function is the Hilbert transform.

11. The apparatus of claim 4 wherein said preselected quantity lies in a set of numbers found by taking an algebraic combination of all possible permutations of said assigned values of one of said data signal elements.

12. Receiver apparatus for use in a digital transmission system wherein elements of a data signal modulate quadrature-related carriers and wherein said carriers are then transformed into a single-sideband signal, said receiver apparatus comprising

means for demodulating said single-sideband signal by extracting said quadrature-related carriers to form elements of a received signal, each received signal element including a selected element of said data signal and a nonzero function of an unselected data signal element; and

means for recovering said data signal elements by altering each received signal element by a plurality of preselected amounts so as to form a set of values for each received signal element and then picking one value from each set in accordance with a preselected criterion.

13. The apparatus of claim 12 wherein said nonzero function is the Hilbert transform of the unselected data signal element.

14. A method of retrieving elements of a data signal wherein said elements modulate quadrature-related carriers and wherein said carriers are transformed into a single-sideband signal, said method comprising the steps of

demodulating said single-sideband signal to form received signal elements by extracting said quadrature-related carriers, said received signal elements being different from said data signal elements due to the

transformation of said carriers into a single-sideband signal; and

recovering said data signal elements by forming at least one estimate of each of said data signal elements by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

15. A transmitter for use in communication systems comprising

means for modulating quadrature-related carrier signals with elements of a data signal to form a double-sideband signal, and

means for transforming said double-sideband signal into a single-sideband signal.

16. A communications system comprising a transmitter and a receiver wherein said transmitter comprises

means for modulating quadrature-related carrier signals with elements of a data signal to form a double-sideband signal, and

means for transforming said double-sideband signal into a single-sideband signal, and

said receiver comprising

means for demodulating said single-sideband signal to form received signal elements by extracting said quadrature-related carriers, said received signal elements being different from said data signal elements due to the transformation of said carriers into a single-sideband signal; and

means for recovering said data signal elements by forming at least one estimate of each of said data signal elements by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

1/2

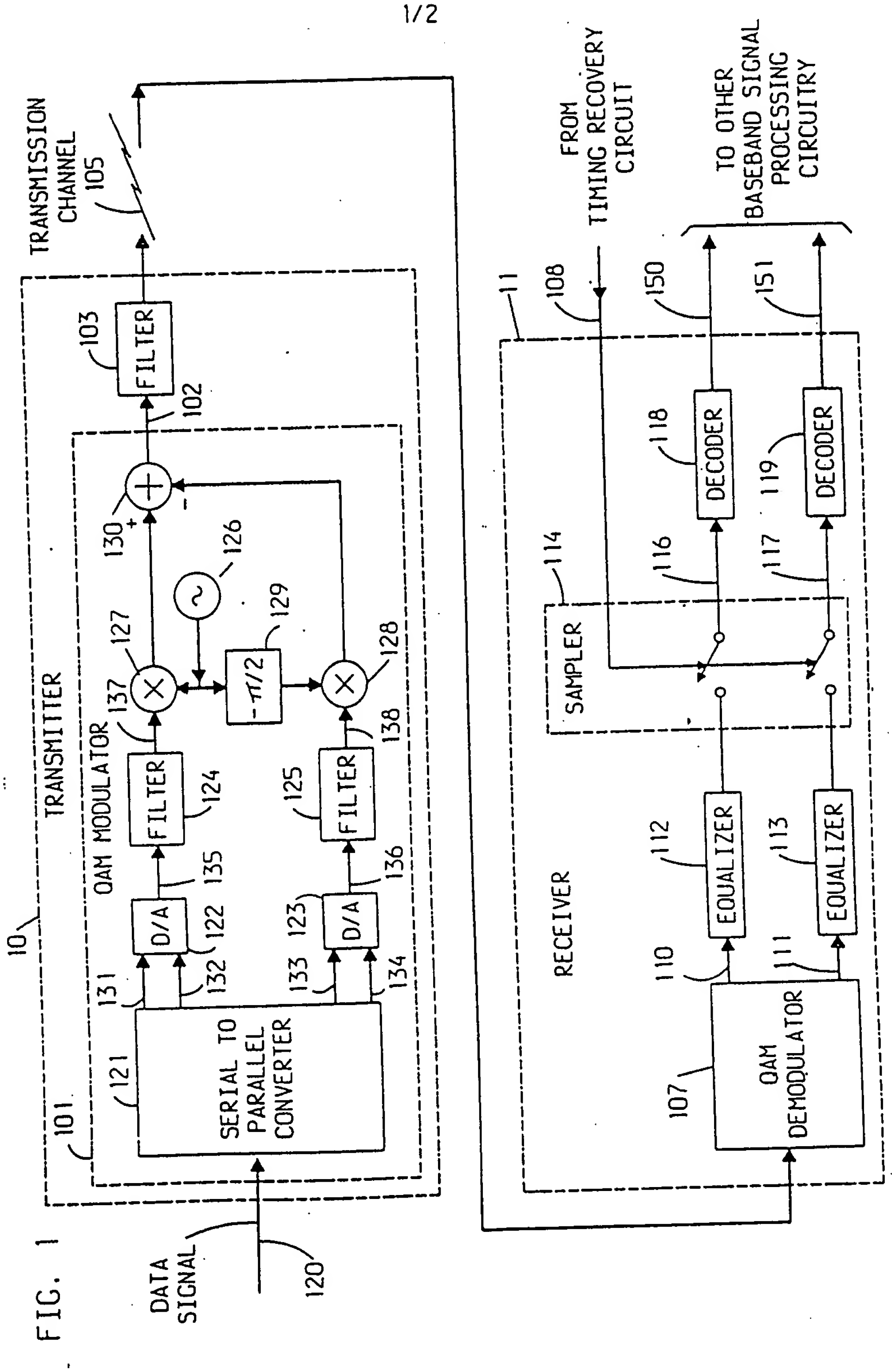

TRANSMISSION CHANNEL
105
10
TRANSMITTER
101
OAM MODULATOR
SERIAL TO PARALLEL CONVERTER
121
131
132
133
134
D/A
122
D/A
123
135
136
FILTER
124
FILTER
125
137
138
127
128
126
-π/2
129
130
+
-
102
FILTER
103
DATA SIGNAL
120
11
RECEIVER
OAM DEMODULATOR
107
110
111
EQUALIZER
112
EQUALIZER
113
SAMPLER
114
116
117
DECODER
118
DECODER
119
108
FROM TIMING RECOVERY CIRCUIT
150
151
TO OTHER BASEBAND SIGNAL PROCESSING CIRCUITRY

FIG. 1

FIG. 2

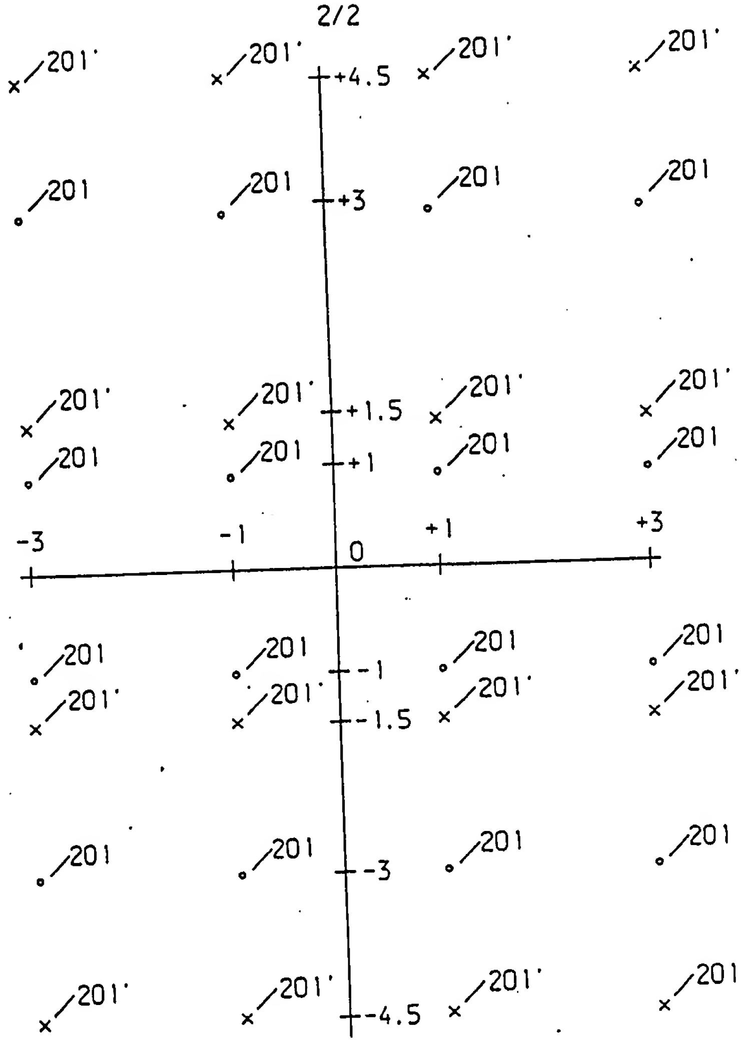
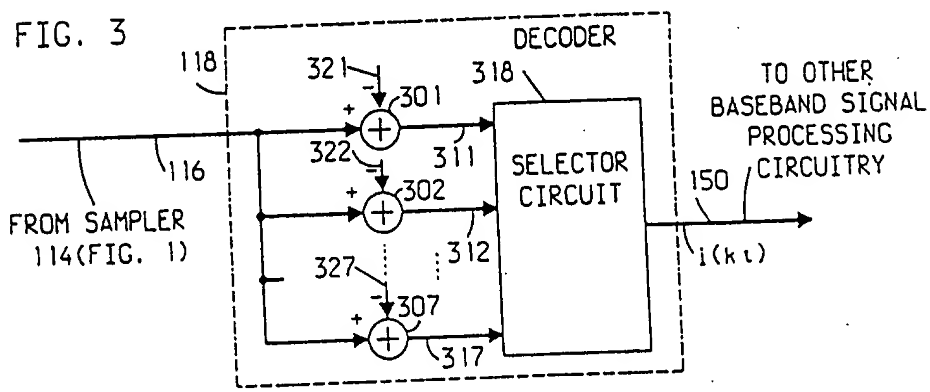

201'
201
+4.5
+3
+1.5
+1
-3
-1
0
+1
+3
-1
-1.5
-3
-4.5

FIG. 3


DECODER
118
321
301
318
322
311
302
SELECTOR CIRCUIT
327
312
307
317
116
FROM SAMPLER 114(FIG. 1)
TO OTHER BASEBAND SIGNAL PROCESSING CIRCUITRY
150
i(kt)

INTERNATIONAL SEARCH REPORT

International Application No PCT/US85/00302

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int. CL.[3] HO4L 25/03 27/02
U.S. CL. 375/39, 43, 77

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	375/39,43,77,80,81 370/20 329/112

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y,P	US, A, 4,470,145 04 September 1984 Williams	1-16
X,P	US, A, 4,461,011 17 July 1984 Lender et. al.	15
Y	US, A, 4,439,863 27 March 1984 Bellamy	1-14, 16
X	US, A, 3,605,017 14 September 1971 Chertok et. al.	15
Y	US, A, 3,522,537 04 August 1970 Boughtwood	1-16
X	US, A, 3,443,229 06 May 1969 Becker	15
A	US, A, 3,849,730 19 November 1974 Ho	1-16

* Special categories of cited documents: [15]
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
12 March 1985	27 MAR 1985
International Searching Authority [1]	**Signature of Authorized Officer [10]**
ISA/US	Stephen Chin

Form PCT/ISA/210 (second sheet) (October 1981)